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Tapered beamforming for concentric ring arrays

Mostafa Nofal[a], Sultan Aljahdali[b], Yasser Albagory[c,*]

[a] Department of Computer Engineering, College of Computers and Information Technology, Taif University, Taif, Saudi Arabia
[b] Department of Computer Science, College of Computers and Information Technology, Taif University, Taif, Saudi Arabia
[c] Department of Information Technology, College of Computers and Information Technology, Taif University, Taif, Saudi Arabia

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ABSTRACT

In this paper, some conventional filtering windows are modified and applied to uniform concentric circular antenna arrays (UCCA) for spatial smoothing and sidelobe reduction. The modified windows are applied to individual rings of the array that will taper the corresponding current amplitudes. The resulted sidelobe level, beamwidth and stability for amplitude errors are discussed for the different proposed tapering windows where it shows a sidelobe reduction to about 49 dB as in the case of Binomial UCCA while the Hamming window shows the most immunity to tapered amplitude errors.

1. Introduction

Concentric circular antenna arrays has an interesting features over other array configurations such as linear one-dimensional or two-dimensional arrays [1–6]. It has widespread use in various applications such as mobile, radar, sonar and direction finding. The array consists of concentric rings each has a number of elements arranged in a circle of certain radius. The sidelobe level in this array is 17.5 dB for most sizes which is less than that of the two-dimensional arrays by 4 dB [5]. A popular array geometry is the uniform concentric circular arrays (UCCA) in which the rings as well as the individual ring elements are separated by almost half of the wavelength [6,7]. If the number of elements of the neighbored rings is incremented by 6 elements [7], the rings will be separated by the nearest distance to a half-wavelength (about 0.4775 of the wavelength). The UCCA at this separating distance will have the optimum radiation pattern and good predicted sidelobes locations but still has higher sidelobes levels which are not suitable in many applications requiring lower sidelobes. The problem of higher sidelobes can be solved through the tapered beamforming techniques in which the array feeding currents are tapered in amplitudes so that it has the maximum value at the center of the array and falls to the minimum at its ends. This technique is studied and performed for the one-dimensional linear arrays and some tapered beamforming techniques such as Binomial, Dolph-Chebyshev and others had proposed [5]. On the other hand, a similar technique which is equivalent to the tapered beamforming in filter design to improve the stopband characteristics (sidelobes) by windowing where some windows such as Triangular, Hamming, Hanning, Blackman, Binomial and others are used [8]. Therefore, in this paper we will modify these filtering windows to be applied to the UCCA for radiation pattern smoothing and sidelobe reduction and the beamwidth variation of the mainlobe is depicted for the different windows. Also the array stability against tapered amplitude errors is discussed for the different tapering windows and the immunity against these errors is shown. The paper is arranged as follows: in Section 2, the array geometry of the UCCA and its related parameters are displayed. Section 3 introduces the different beamforming windows applied for tapering the UCCA and Section 4 discusses the sidelobe level and beamwidth variations. Section 5 discusses the stability of the array against amplitude errors and finally, Section 6 concludes the paper.

2. Uniform concentric circular arrays (UCCA)

Fig. 1 displays the geometry of a concentric circular antenna array consisting of M concentric rings each has a number of elements N_m where $m = 1, 2, \ldots, M$. The elements in each ring are assumed to be omnidirectional and the interelement separation is almost half of the wavelength which can be obtained if the number of elements in the rings is incremented by 6 [7] or:

$$N_{m+1} = N_m + 6 \tag{1}$$

The separating distance of $\lambda/2$ is chosen to have a radiation pattern that has one mainlobe and no grating lobes which appear at larger separating distances. Also, the radiation pattern has wider beamwidth if we used a smaller interelement separation which reduces the efficiency of the array. If the mutual coupling between the neighbored elements is neglected, we can determine an expression for the array factor at any direction if we know the weights of the rings and the array steering matrix.

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* Corresponding author. Tel.: +966 53 714 3811.
E-mail address: y.albagory@tu.edu.sa (Y. Albagory).

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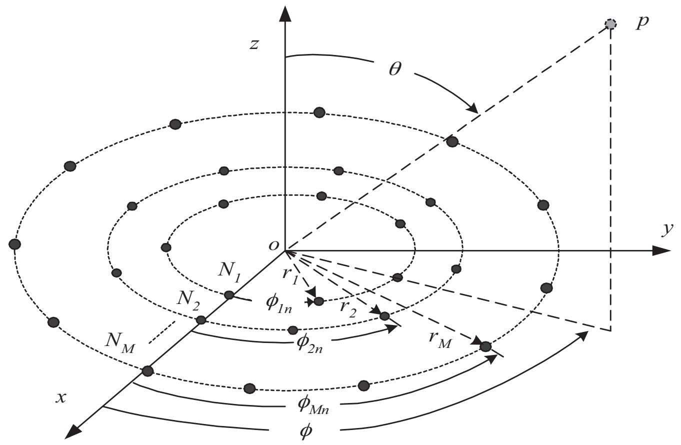

Fig. 1. Concentric circular arrays (CCA).

For the UCCA, the array steering matrix can be given by [7]:

$$AS(\theta,\phi) = [S_1(\theta,\phi) S_2(\theta,\phi), \ldots, S_m(\theta,\phi), \ldots, S_M(\theta,\phi)] \tag{2}$$

where each column in $AS(\theta,\phi)$ represents the ring steering vector which generally for the mth ring is given by:

$$\begin{aligned} S_m(\theta,\phi) = {} & [e^{jkr_m \sin\theta \cos(\phi-\phi_{m1})} e^{jkr_m \sin\theta \cos(\phi-\phi_{m2})}, \ldots, \\ & e^{jkr_m \sin\theta \cos(\phi-\phi_{mn})}, \ldots, e^{jkr_m \sin\theta \cos(\phi-\phi_{mN_m})}]^T \end{aligned} \tag{3}$$

where $k = 2\pi/\lambda$ and this mth ring has a radius r_m and number of elements N_m.

In tapered beamforming, we multiply the array steering matrix with a tapering weight matrix $W(\theta,\phi)$ given by:

$$\begin{aligned} W(\theta,\phi) = {} & [\alpha_1 S_1(\theta_o,\phi_o) \alpha_2 S_2(\theta_o,\phi_o), \ldots, \\ & \alpha_m S_m(\theta_o,\phi_o), \ldots, \alpha_M S_M(\theta_o,\phi_o)] \end{aligned} \tag{4}$$

where for $m = 1, 2, \ldots, M$, α_m is the amplitude coefficients of the mth ring current and $S_m(\theta_o,\phi_o)$ is the ring steering vector at the mainlobe direction (θ_o,ϕ_o). From Eq. (4), we notice that all elements in an individual ring is weighted by the same value therefore the array factor will be given by

$$G(\theta,\phi) = SUM\{W(\theta,\phi)^H AS(\theta,\phi)\} \tag{5}$$

where the SUM operator is the summation of the elements of the resulted matrix and H is the complex conjugate transpose.

In this section, some conventional windows are modified and applied for amplitude tapering of the UCCA. These windows are well defined for filtering applications such as finite impulse response (FIR) filter designs such as Triangular, Hamming, Hanning, Blackman and Binomial windows. It had showed the possibility to reduce the sidelobe-to-mainlobe ratio in the filter magnitude response. Conventional one-dimensional tapered arrays have tapered the currents of the individual array elements, while in the case of UCCA, we consider the individual ring to be equivalent to an element of the one-dimensional linear array. The following sections defines these possible amplitude tapering windows.

3. Tapering windows for UCCA

In this section, some conventional windows are modified and applied for amplitude tapering of the UCCA. These windows are well defined for filtering applications such as finite impulse response (FIR) filter designs such as Triangular, Hamming, Hanning, Blackman and Binomial windows. It had showed the possibility to reduce the sidelobe-to-mainlobe ratio in the filter magnitude response. Conventional one-dimensional tapered arrays have tapered the currents of the individual array elements, while in the case of UCCA, we consider the individual ring to be equivalent to an element of the one-dimensional linear array. The following sections defines these possible amplitude tapering windows.

3.1. *Uniform feeding window*

The uniformly fed UCCA has the same amplitude coefficients which is the unity or

$$\alpha_m = 1, \quad m = 1, 2, \ldots, M \tag{6}$$

these coefficients give the smallest beamwidth compared with any other window and the highest sidelobe level of 17.5 dB as shown in Fig. 2a for a typical array of $N_1 = 5$ and $M = 10$.

3.2. *Triangular amplitude tapering*

In Triangular tapering, the amplitude weighting follows a triangular function that equals zero at a virtual ring number $M + 1$. The rings amplitude coefficients for this scheme is given by:

$$\alpha_m = \frac{(M - m + 1)}{M}, \quad m = 1, 2, \ldots, M \tag{7}$$

where m is the ring number in the array. The innermost ring has a weight value $\alpha_1 = 1$ while the outermost ring has a weight value of $\alpha_M = 1/m$.

Fig. 2b displays a typical radiation pattern of the same array configuration as in Fig. 2a.

3.3. *Hamming amplitude tapering*

The Hamming window [8] used for filter applications are modified here and gives the following rings coefficients for a UCCA of M rings:

$$\alpha_m = 0.54 - 0.46\cos\left(\frac{\pi(m - M - 2)}{M + 1}\right), \quad m = 1, 2, \ldots, M \tag{8}$$

Fig. 2c displays the radiation pattern of Hamming UCCA where the sidelobe level will be 29.5 dB.

3.4. *Hanning amplitude tapering*

The Hanning window [8] is very similar to the Hamming window and provides an array coefficients that are modified to suit the application of the UCCA and is given by:

$$\alpha_m = 0.5 - 0.5\cos\left(\frac{\pi(m - M - 2)}{M + 1}\right), \quad m = 1, 2, \ldots, M \tag{9}$$

Fig. 2d depicts the radiation pattern of the Hanning tapered array which has a very similar value of the sidelobe level as in the Hamming array.

3.5. *Blackman amplitude tapering*

Invariant to the last tapering schemes, Blackman window [8] provides another cosine term for further sidelobe reduction. The modified coefficients function for the UCCA tapering is given by:

$$\begin{aligned} \alpha_m = {} & 0.42 - 0.5\cos\left(\frac{\pi(m - M - 2)}{M + 1}\right) \\ & + 0.08\cos\left(\frac{2\pi(m - M - 2)}{M + 1}\right), \quad m = 1, 2, \ldots, M \end{aligned} \tag{10}$$

The radiation pattern for this type of tapering is shown in Fig. 2e which reduces the sidelobe level to 38 dB.